UROP Proposal

Near-Field Scanning Thermoreflectance Microscopy for Nanoscale Temperature Measurement

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Problem/Topic Statement of Proposed Research

My UROP proposal aims to realize optical-based thermometry with spatial resolution on the order of 10 nm by integrating scattering-type near-field scanning optical microscopy (s-NSOM) with thermoreflectance thermometry. Under the supervision of Prof. [redacted] in Mechanical Engineering and his Ph.D. student, I will examine the temperature dependence of the near-field light scattering and compare it with the known far-field optical thermoreflectance behavior. To test the hypothesis, we will measure the intensity of tip-scattered light from different surfaces, including silicon (semiconductor), gold (metal) and silicon dioxide (dielectric), as a function of temperature. Based on the obtained temperature dependence of tip-scattered light, the temperature distribution around a microheater will be mapped and compared with theoretical predictions. Successful completion of the proposed research will enable sub-10-nm thermometry, which will cast a very fundamental question on the local thermodynamic equilibrium of nanoscale temperature measurements.

Research Background

Nanotechnology is defined as the manipulation of matter with at least one dimension in the range of 1 to 100 nanometers by the National Nanotechnology Initiative. On this scale, quantum mechanical properties of matter can significantly deviate from continuum-based physics. Nanotechnology has broad ranging applications in industrial, military, medical, and currently unimagined realms. The measurement, quantization and understanding of these nanoscale properties is essential to the advancement of all nanotechnology applications, and the promises of nanotechnology have persuaded world governments to invest billions of dollars into research and development.[2] Nanotechnology has already had significant and permanent impact on society and its effects will grow.

Thermoreflectance microscopy is a promising optics-based thermometry technique that precisely measures temperatures or thermophysical properties by utilizing the correlation between the reflectance of light and temperature.[3] Previous studies have revealed that the light reflectance decreases linearly as temperature increases due to the temperature-dependent refractive index of a substrate.[4,5] However, since conventional thermoreflectance microscopy makes use of far-field optics, its spatial resolution is limited by the light wavelength and the numerical aperture of an objective lens, referred to as the Abbe diffraction limit.[6] For example, the spatial resolution of thermoreflectance microscopy is ~0.7 μm when using a 785 nm near-infrared laser.[4] Sub-wavelength imaging, including thermoreflectance, is thus extremely challenging with a conventional far-field microscope.

Scattering-type near-field scanning optical microscopy (s-NSOM) is novel scanning probe microscopy that breaches the diffraction limit of optical images by collecting light scattered from an oscillating probe tip. The metal-coated tip acts as an optical nano-antenna that highly confines light to its apex.[7-9] When the tip is in proximity to a surface, strong near-field interactions induce tip-enhanced scattering of evanescent electromagnetic waves at the tip apex. It should be noted that the spatial resolution of tip-enhanced scattering depends not on the wavelength of light but on the tip sharpness. Moreover, since tip-enhanced light scattering is a result of tip-substrate near-field interactions,[10-13] s-NSOM can measure the optical properties, particularly the complex refractive index of a substrate with nanoscale resolution. s-NSOM has also provided interesting insights into the electronic, thermal and mechanical properties of graphene layers by allowing rapid, non-invasive mapping of graphene grain boundaries.[5,14]

The main objective of the proposed research is to extend the unique capability of s-NSOM in measuring nanoscale optical properties to nanoscale thermoreflectance microscopy by testing the hypothesis that tip-enhanced light scattering is analogous with thermoreflectance and thus can be used to measure temperature at nanoscales. Nanoscale thermometry is a relatively unexplored research area that has numerous applications over a range of nanotechnologies. Nano-electronic devices and integrated circuits often fail due to local hot spots which are typically sub-100-nm in size. Current optics-based thermometry schemes, such as infrared (IR) thermometry, Raman spectroscopy, and thermoreflectance microscopy, cannot achieve a sub-100-nm spatial resolution owing to the diffraction limit, measurement interference, and other instrumentation issues.

Activities and Timetable:

To accomplish the proposed research goal, I propose the following specific activities:

Activity 1: Learn the operating procedures of the AFM to take nanoscale topographical images

Atomic force microscopy (AFM) is a powerful tool for nanoscale topographical imaging. The surface characteristics of a sample can be measured by oscillating a cantilever probe near the sample surface (tapping mode). Changes in the amplitude of the oscillations – measured using interferometric laser detection – correspond with changes in the surface roughness. By scanning the sample surface, a topographical image is generated. In order to complete this research project, I must become proficient in AFM setup and procedures. I will begin by learning to precision mount cantilever probes. The cantilever probes must be mounted with micron precision to allow for interferometric laser detection. Next, I will learn to operate the AFM software. The AFM control system (RHK Technologies R9) is exceptionally powerful and complex. I must understand each component – including filters, lock-in amplifiers, A/D and D/A converters – and the logic behind electrical interconnections. In addition, I will acquire signal detection, conditioning, noise reduction, PID control, high vacuum and ultra-high vacuum environment experience which will be beneficial throughout my career. I will then proceed to take AFM images with sub-nanometer resolution until I become adept at AFM setup and calibration.

<u>**Activity 2**: Learn to take optical nanoscale images using s-NSOM</u>

The difficulty with s-NSOM is a large elastic scattering background.[15] The near-field interaction diminishes over distances comparable to the tip radius (r) while the background diminishes on the light wavelength scale (λ>>r); therefore, the oscillating AFM tip rapidly changes the near-field signal while the background changes relatively slowly. By operating the AFM tip in tapping mode, higher harmonics in the near-field signal are created, and by detecting the higher harmonics, partial background suppression is achieved. Complete background elimination is accomplished by interfering a phase-modulated synthetic reference wave (SRW) with the scattered wave, typically referred to as psuedoheterodyne detection technique.[15] If the reference modulation frequency (M) is lower than the AFM tip vibration frequency (Ω), each of the scattered signal higher harmonics split into sidebands (**Figure 1**).[14,15] The background does not appear at the sideband frequencies and by extracting the signal from these sidebands, pure near-field signal recovery is possible.[15]

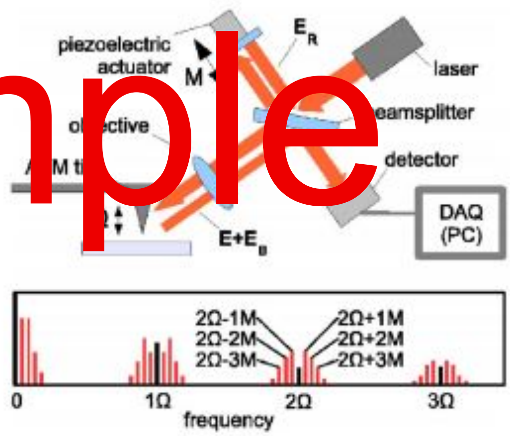

Figure 1: Interferometric detection of near-field and background scatterings from a s-SNOM probe employing a phase-modulated synthetic reference beam and detected signal spectrum

I will fully understand the optics involved with s-NSOM, pseudoheterodyne detection, and higher harmonic demodulation techniques. I will learn to precision align the components on the optical bench, manipulate the piezo-controlled optics and their control software as well as integrate multiple light sources. I will proceed to take tip-scattered near-field images until I have gained sufficient skill.

Activity 3: Integrate near-field optics with thermoreflectance thermometry

We have developed a high-vacuum scattering-type near-field scanning optical microscope (HV-sNSOM). Our s-NSOM platform integrates a mirror-reflection scheme (see **Figure 2**) with a scanning probe head in a high-vacuum chamber, allowing the optical access of external light onto a tip in a highly precise manner – it is one of only two such setups in the world. Our setup is equipped for pseudoheterodyne and higher harmonic demodulation for complete background elimination. Furthermore, the sample stage of the HV-sNSOM is interfaced with a temperature controller for precise control of the surface temperature – which is unique to our HV-sNSOM.

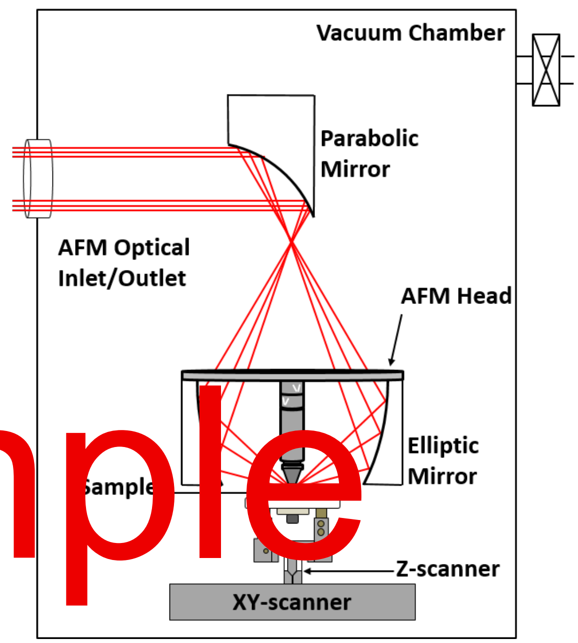

Figure 2: The optical pathway to the sample and AFM tip

Using our HV-sNSOM, I will measure the temperature dependence of near-field scattered light and compare the experimental results with the known far-field thermoreflectance behavior for different materials. I will proceed to fabricate and characterize a microheater. Using the obtained temperature calibration, the temperature distribution around the microheater will be mapped and compared with theoretical predictions. Successful completion of microheater thermal mapping will enable nanoscale thermal mapping of other systems, such as nano-electronic devices and integrated circuits. I will begin writing a manuscript to submit for publication upon the completion of activity two.

The timetable of each activity can be found in the following table:

The proposed research tasks will be accomplished by following the timetable shown below:

Near-field thermoreflectance microscopy	Start Date	End Date	Duration	Predecessors
Activity 1: Operate the AFM	**08/24/15**	**09/18/15**	**20**	
Learn how to precision mount cantilever probes for interferometric laser detection	08/24/15	08/28/15	5	
Learn how to mount tuning fork probes	09/07/15	09/11/15	5	
Learn how to operate the AFM software and control system	08/31/15	09/04/15	5	2
Learn how to operate the high-vacuum and ultra-high-vacuum conditions	08/31/15	09/04/15	5	2
Learn how to calibrate the AFM scanner	09/07/15	09/11/15	5	5
Take AFM images with sub nanometer resolution	09/14/15	09/18/15	5	6
Activity 2: Take optical nanoscale images using s-NSOM	**09/21/15**	**10/09/15**	**15**	**1**
Learn how to align components on optical bench	09/21/15	09/25/15	5	
Learn how to align the AFM piezo controlled optics	09/21/15	09/25/15	5	
Learn how to integrate multiple light sources (visible,IR)	09/28/15	10/02/15	5	10
Take tip-scattered near-field images	10/05/15	10/09/15	5	11
Obtain near-field optical images with sub-100-nm resolution	**09/21/15**	**09/25/15**	**5**	**#REF**
Implement laser alignment for experimentation	09/21/15	09/25/15	5	
Image s-NSOM calibration grating with 2nd harmonic demodulation	09/21/15	09/25/15	5	
Implement pseudoheterodyne background suppression method	09/21/15	09/25/15	5	
Obtain background free near-field image	09/21/15	09/25/15	5	
Activity 3: Integrate near-field microscopy with thermoreflectance temperature measurements	09/28/15	10/23/15	20	13
Operate sample stage temperature controller	09/28/15	09/30/15	3	
Measure near-field optical signal dependence on temperature	10/01/15	10/08/15	6	19
Compare near-field and far-field thermoreflectance signals	10/09/15	10/23/15	11	20
Fabrication and characterization of microheater	09/28/15	10/09/15	10	
Perform near-field thermoreflectance measurement for temperature distribution about the microheater	10/12/15	10/16/15	5	25
Interpretation of results	10/19/15	10/23/15	5	26
Write the manuscript	09/28/15	11/13/15	35	17
Submit work for publication	12/21/15	12/25/15	5	
Write UROP Final report	12/07/15	12/18/15	10	

For the full Gantt chart, visit the following link:

Gantt Chart for Near-field Thermoreflectance Thermometry or go to the following URL: https://app.smartsheet.com/b/publish?EQBCT=74cd555c84354f8aa[illegible]7ddae1b3290699

Relationship to Mentor's Expertise:

Professor [redacted] in Mechanical Engineering will serve as my research mentor for the proposed research. One of Professor [redacted]'s research areas is tip-based nanoinstrumentation and nanoengineering based on his expertise in scanning probe microscopy and near-field radiation. He works on the energy interactions between nanostructures and consequent thermal, electrical, and optical responses. He has published more than 25 journal articles in this research area and presented at numerous conferences. Prof. [redacted]'s [redacted] has equipped a unique high-vacuum atomic force microscope (HV-AFM) that allows for optical access of external light sources. This instrument will be core for my research on the nanoscale thermoreflectance thermometry. My proposed research project will be directly within Prof. [redacted]'s areas of expertise allowing him to be the optimal mentor. I recently completed Thermodynamics II (MEEN 3600) under the direction of Prof. [redacted]; I thoroughly enjoyed my experience as his student and his teaching style. In addition, Mr. [redacted], one of Prof. Park's Ph.D. students, will aid with my research. He has gained expertise on the HV-AFM during his Ph.D. studies, and will closely work with me and teach me on AFM operations. I will have a weekly meeting with Prof. [redacted] to discuss my research progresses and get his feedback. In addition, I will attend weekly group meetings to learn new research progresses from other students and practice effective communication skills.

<u>Student Goals</u>

Although the [redacted] is representing the Mechanical Engineering department, the theoretical nature of the research requires strong physics crossover understanding. As a mechanical engineering and physics double major, I feel this research project is uniquely tailored to my strengths and interests. A research position that delves into both of my majors is an exceptional opportunity for me. As a freshman, I worked in the Organic Light Emitting Diode (OLED) Lab in the Physics Department studying luminosity and spectra dependence on magnetic fields and temperature. That experience cemented my desire to continue my education past a bachelor's degree and I intend continue on into graduate school for Mechanical Engineering as soon as I complete my double major (Fall 2016). I am committed to working an organized, efficient and insightful research project and capping my accomplishments with a published article. In addition to strengthening my appeal to graduate school, publishing an article would be an exceptional growth opportunity for me personally and would help professionally prepare me to pursue a career in research and development of emerging technologies. In addition, many opportunities for research and development will be in the field of nanotechnology. Developing nanoinstrumentation skills in the [redacted] would prepare me for those opportunities in a way that classes alone cannot.

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